SLR2000 Technical Overview, Status, and Schedules

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Code Y SLR2000 Review

June 1, 2001

SLR2000 Historical Background & Past Reviews

- **November, 1993:** Faced with an increasing operational workload and falling SLR budgets, Dr. David Smith (GSFC Code 920) asks John Degnan to "think outside the box" and develop concept for new lower cost system.

- **February 1994:** Original SLR2000 concept, limited to LAGEOS (< 8500 km slant range) and lower satellites, was first presented to, and endorsed by, the NASA Belmont SLR Workshop.

- **1994-1997:** Inhouse and contracted conceptual studies performed using a small amount of Code YS R&D funding (~$50K total). During this period, GSFC was directed by Code YS (Dr. Miriam Baltuck and Dr. John LaBrecque) to extend SLR2000 ranging capability to GPS satellites (22,000 km slant range). New specification required larger laser, telescope, and tracking mount.

- **September 1996:** SLR2000 concept was presented to international "Blue Ribbon" panel assembled by Dr. Baltuck, Code YS, to determine the future of NASA SLR (Chairman: Professor Irwin Shapiro, Harvard).

- **April 1997:** Shapiro Committee final report endorsed continued but reduced NASA SLR operations. The committee also recommended $1.25M/yr be allocated by NASA HQ for SLR2000 development.

- **August 1997:** SLR2000 technical approach reviewed and approved by GSFC MTPE Office (Dr. Robert Price). First substantial funding provided.

- **September 1999:** After breakup of MTPE, funding responsibility was transferred to Code YO and ultimately back to Code YS. NASA HQ review of SLR2000 progress held by Dr. Earnie Paylor.

- **March 2000:** briefing to Dr. Jack Kaye and John LaBrecque, Code YS

- **October 2000:** SLR2000 project technical approach, progress, and resources reviewed by GSFC Management Council chaired by GSFC Deputy Director, W.F. Townsend.

- **June 2001:** Code Y review requested by Dr. Ghassem Asrar and chaired by Thomas Magner. 2

SLR2000: Motivation

- **SLR provides unique and important science through its use of passive "cannonball" geodetic satellites**
  - **defines Earth center-of-mass and scale (GM) in International Terrestrial Reference Frame (ITRF)**
  - **Contributes to a wide range of Earth Science applications**
- **The SLR range observable is the most accurate (sub-cm), is unambiguous, and is insensitive to tropospheric and ionospheric path delays for Precise Orbit Determination (POD) applications.**
  - **Especially important to microwave and laser altimetry missions (e.g. ERS-1 and 2, TOPEX/Poseidon, GFO-1, ICESat, VCL, etc)**
- **SLR will be tracking 30 international spacecraft by the end of 2002.**
- **The SLR ground segment is more expensive than competing space geodetic techniques (e.g. GPS) and funding has been dropping over the last decade while the customer base continues to rise almost exponentially.**
- **SLR operations costs can be greatly reduced through greater standardization, automation, and maximum utilization of COTS parts.**
- **New technologies are available which can reduce system complexity and cost and improve reliability**

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SLR 2000 Program Objectives/Requirements

- Unmanned, eye-safe operation
- 24 hour laser tracking to satellites up to 22,000 Km slant range (GPS, GLONASS, ETALON)
- One cm (1σ RMS) single shot ranging or better
- ~1 mm precision normal points to LAGEOS
- Mean Time Between Failures: >4 months
- Operational Temperature Range: 20ºF to 120ºF
- Automated two-way communications with central processor via Internet with modem backup
- Free of optical, electrical, and chemical hazards
- Reduce system replication cost to ~$1M per system
- Reduce system operations costs to ~ $3.5M/yr

SLR2000 Technical Approach

- **Use off the shelf components where possible**
  - **Allows rapid component replacement and outsourcing of engineering support**

- **To constrain costs, use TLRS-size telescopes (D$\leq$40 cm)**
  - **Constrains cost of telescope (\$ α D$^{2.3}$) and optical tracking mount**
  - **Implies eyesafe transmitted energy <135 μJ per pulse at 532 nm**
  - **Compensate for 1000-fold reduction in transmitted energy by increasing laser fire rate to kHz rates and reducing beam divergence**

- **For failsafe reliability, choose passive over active approaches and simple over complex solutions where practical; e.g.**
  - **passively Q-switched microlaser at 2 KHz (runs off DC supply)**
  - **passive T/R switch to eliminate mechanical systems and high voltage**
  - **choose eyesafe beams over active radars**

- **Use post-detection Poisson Filtering techniques to extract ranging signal from noise and provide subarcsecond pointing corrections**

SLR2000 BLOCK DIAGRAM
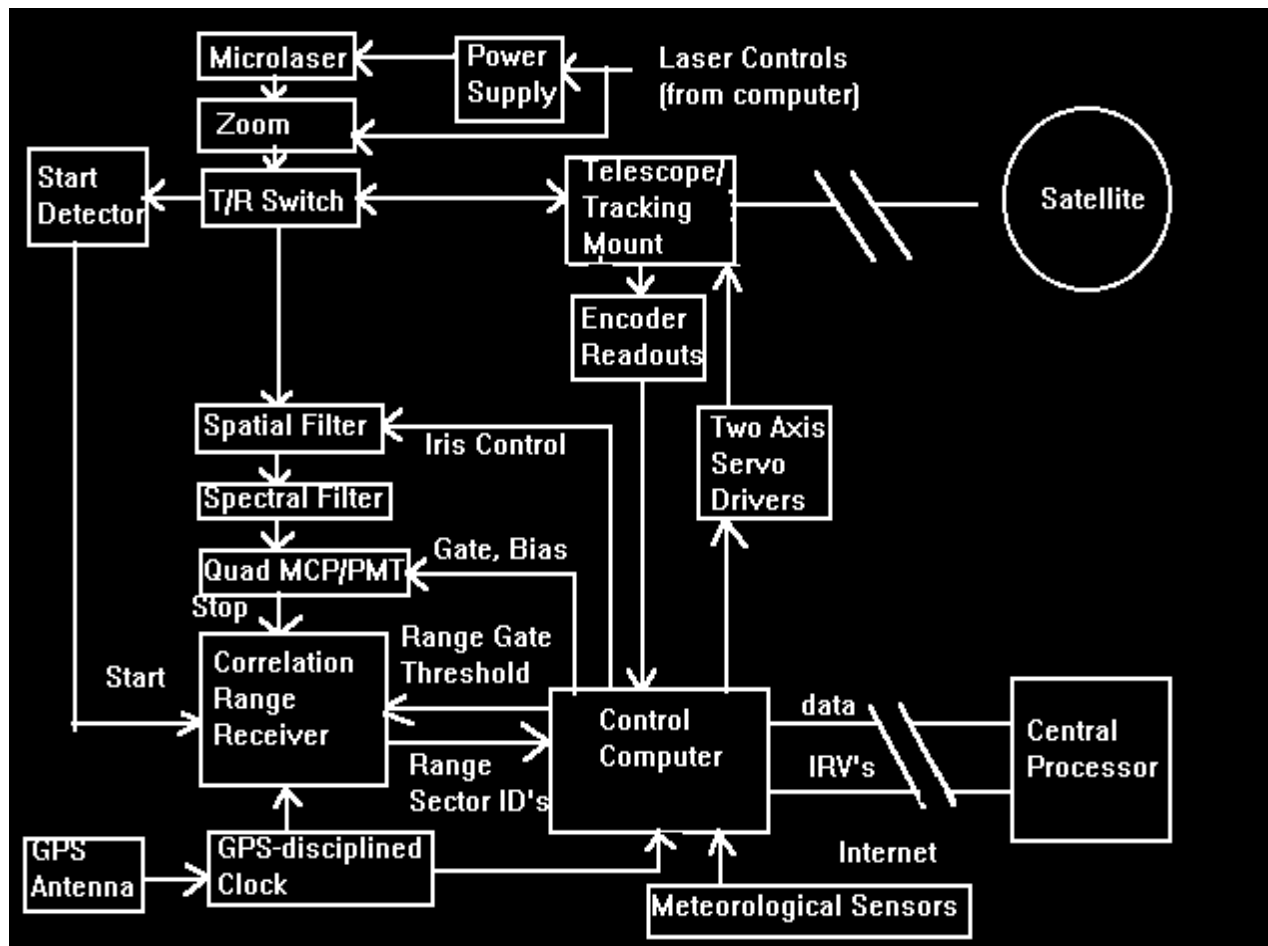
SLR2000 Civil Service & Contractor Workforce

- **Civil Service (all Code 920.3, all part-time)**
  - **John Degnan, Program Manager, Senior Systems Engineer, 37 years experience in SLR**
  - **Jan McGarry, Senior Software Engineer, 27 years experience in SLR software**
  - **Tom Zagwodzki, Senior I&T Engineer, 28 years experience in SLR**
- **Support Contractors**
  - **Honeywell Technology Solutions Inc.(SLR/VLBI Mission Contractor)**
    - **Shelter, Pad, Dome Controller, Security Systems, Power & Communications**
    - **Gating and Ranging Electronics Support**
    - **General I&T Support**
    - **Data And Analysis (DAN) Software Support**
    - **Development Subcontracts**
      - **Photek Inc. (Quadrant Microchannel PlatePhotomultiplier)**
      - **Xybion Inc. (Arcsecond Precision Tracking Mount)**
      - **EOO Inc. (Analysis Support)**
  - **Fairchild/Orbital Sciences Corporation (Code 500 Task Order Contract)**
    - **40 cm diameter off-axis telescope**
    - **Optical Transceiver**
  - **Raytheon STX (Code 900 Task Order Contract)**
    - **"Smart" Meteorological System and Supporting Software**
    - **Pseudo-OPerator (POP) Software Support**
  - **University of Texas Center for Space Research**
    - **Remote Access Terminal (RAT) Software Support**
  - **MIT Lincoln Laboratory (Interagency Funds Transfer USAF)**
    - **Prototype Microlaser Oscillator**
  - **Q-Peak Inc**
    - **Brassboard Microlaser OSC/AMP Transmitter(SBIR Phase II)**
    - **Upgraded Field Transmitter**
  - **Boeing Corporation**
    - **Project scheduling support.**

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SLR2000 Unique Features

- **Totally Eyesafe Operation**
  - **Uses low energy microlasers (130 μJ/pulse) at high repetition rates (2 kHz)**
  - **Laser beam fills 40 cm transmit/receive telescope to meet OSHA radiation standards**
  - **No aircraft safety radars needed**
- **Sub-unity Signal-to-Noise Ratios (SNR) during daylight operations**
  - **Mean signal strength: <<1 photoelectron per laser fire**
  - **Uses Post-Detection Poisson Analysis to extract satellite signal from noise background in real time, center signal in range gate, and reduce gate width**
  - **Photon-counting quadrant detector/multichannel receiver provides both high resolution ranging (1 mm precision) and sub-arcsecond angular tracking error feedback to mount.**

LAGEOS
Range O-C Plot

NOISE
SIGNAL
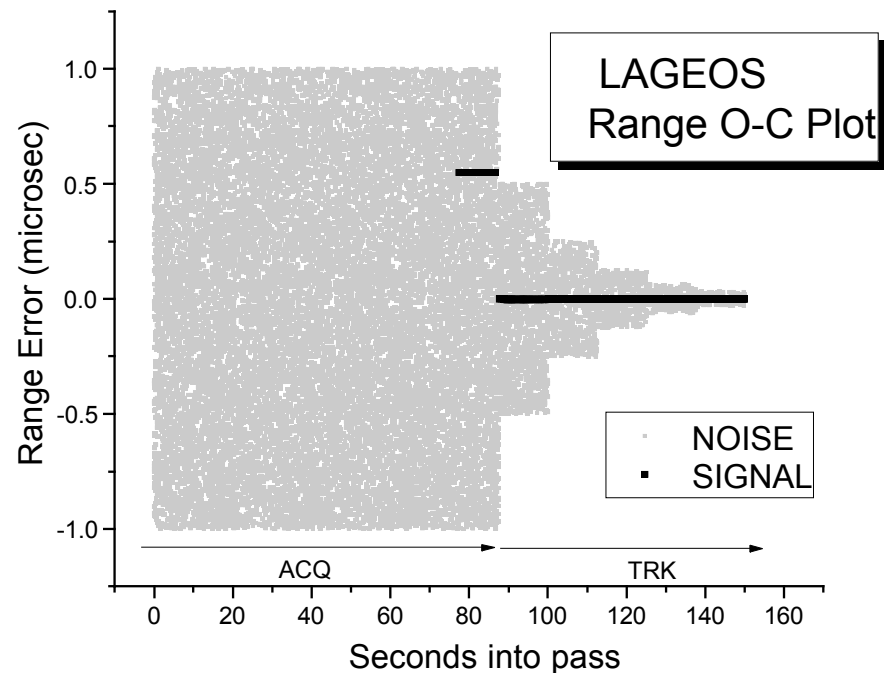
LAGEOS Acquisition Simulation at 8600 km Slant Range (20º elevation)
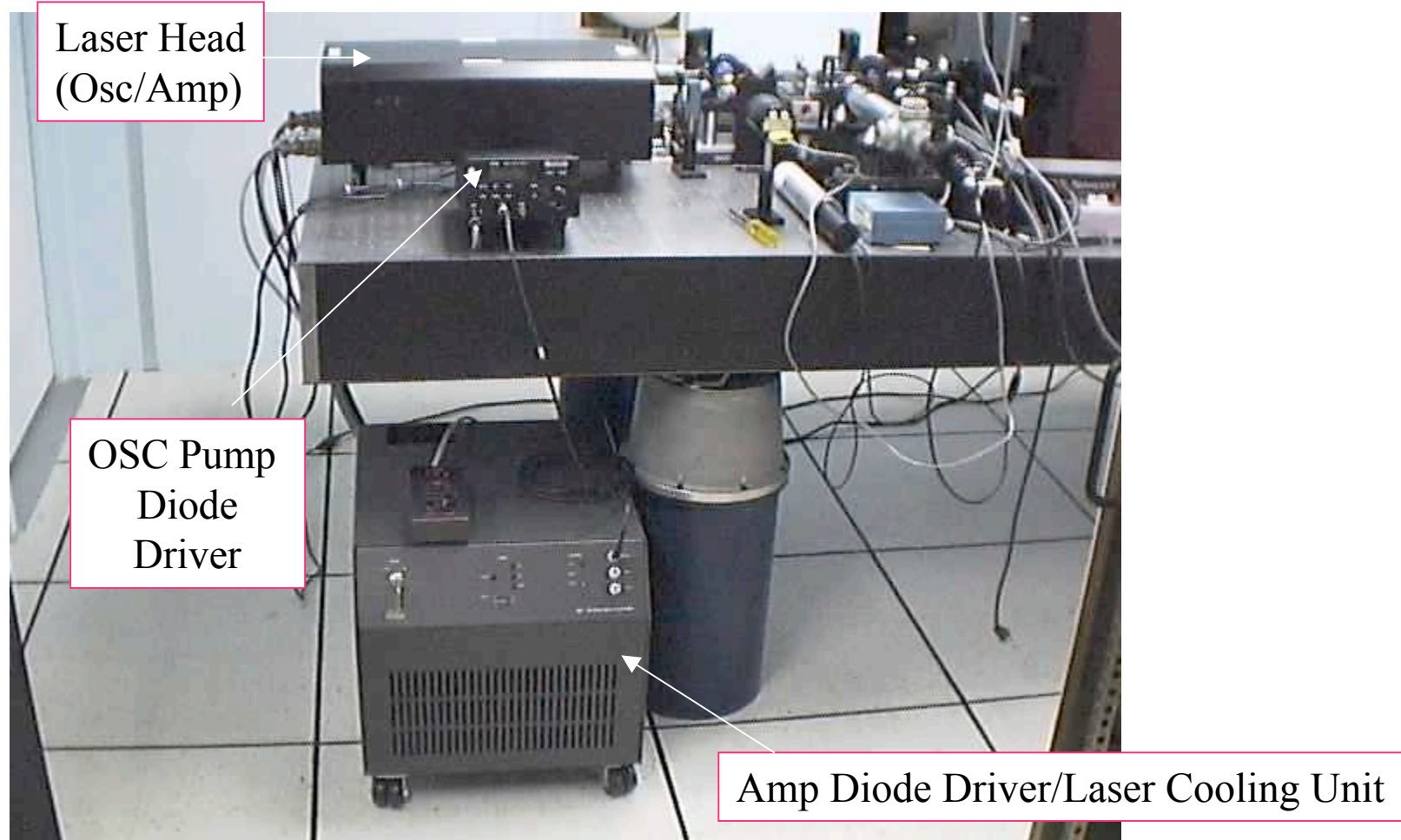
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SLR2000: Progress FY98-FY01

- **Several new "enabling" technologies for SLR2000 were developed/procured in FY98-99**
  - **Microlaser Transmitter**
  - **Quadrant Microchannel Plate Photomultiplier**
  - **"Smart" Meteorological Station**
  - **Multikilohertz Event Timer and Range Gate Generator**
  - **GPS-disciplined rubidium time and frequency reference**
  - **Signal extraction algorithms for daylight tracking at single pe level**
- **Major subsystems were designed and fabricated in FY99-01**
  - **Shelter and Tracking Dome**
  - **40 cm Off-Axis Telescope Assembly**
  - **Arcsecond Precision Tracking Mount (undergoing mods to improve tracking accuracy)**
  - **Microlaser Oscillator/Amplifier Brassboard (Phase II SBIR)**

High Power Microlaser

3 INCHES
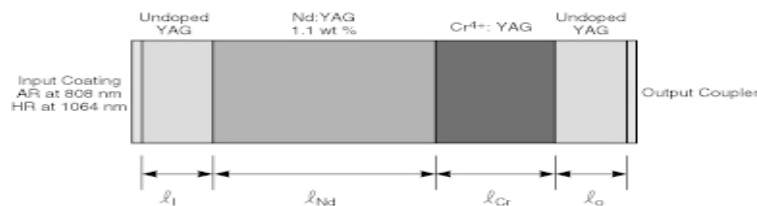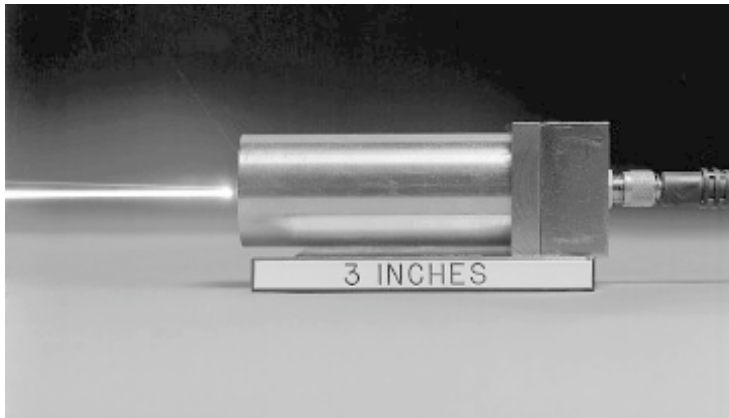
- **Several devices jointly developed by NASA/GSFC and MIT/Lincoln Lab**
- **Power:**
  - **>1 Watt @1064 nm**
  - **>600 mW @532 nm**
- **Repetition Rate: up to 16 kHz**
- **Energy: up to 250 μJ/pulse**
- **Pulsewidths: 300 to 2200 psec**
- **Pumped by single GaAs diode laser array at 808 nm (< 11 W)**
- **Passively Q-switched**
- **Monolithic Structure**
  - **Thermally bonded Nd^{3+}:YAG, Cr^{4+}:YAG, and undoped YAG layers**
  - **Coatings applied to crystals**
  - **laser resonator < 11 mm in length**
  - **Can't misalign**

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SLR2000 Brassboard Transmitter (developed under Phase II SBIR)

Laser Head (Osc/Amp)

OSC Pump Diode Driver

Amp Diode Driver/Laser Cooling Unit

Final field unit will be air-cooled and laser head will be repackaged into smaller box with upgraded microlaser oscillator.

SLR2000 High Speed, Photon-Counting, Quadrant Detector
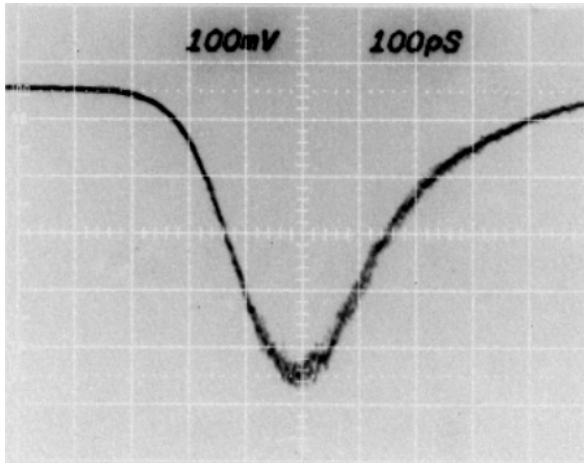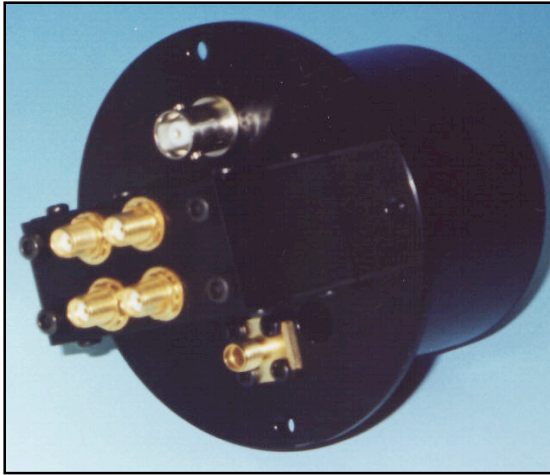
Characteristics:

- **Microchannel Plate Photomultiplier**
- **Active cathode area: 12 mm diameter**
- **Cathode material: Multialkali**
- **Quantum Efficiency: >13%**
- **Minimum Gain: 3×10^{6} for single pe detection**
- **Segmented quadrant anode with separate SMA connectors**
- **Risetime at anode (10% -90%): <140 psec all quadrants**
- **Max time delay between quadrants (symmetric design): < 8 psec**
- **Timing jitter < 28 psec RMS, <40 psec between channels**
- **Externally gated at 2 KHz rate**

Simultaneously provides high precision timing of single photon events and fine angular pointing corrections in photon-counting mode !

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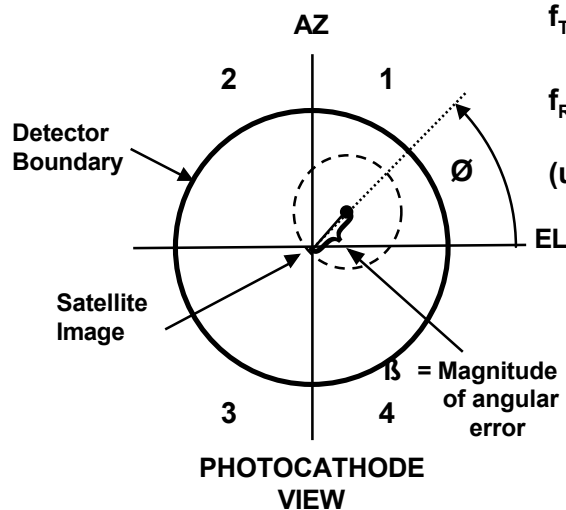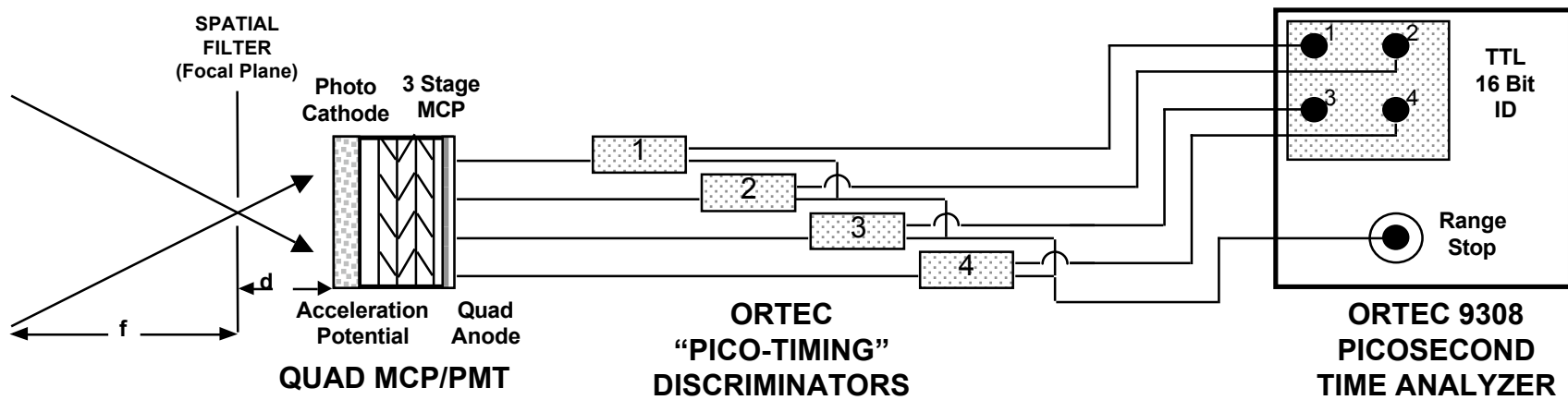# SLR 2000: Simultaneous Ranging And Angular Tracking In Photon Counting Mode

SPATIAL FILTER (Focal Plane)

Photo Cathode

3 Stage MCP

Acceleration Potential

Quad Anode

QUAD MCP/PMT

1

2

3

4

ORTEC "PICO-TIMING" DISCRIMINATORS

TTL 16 Bit ID

1   2
3   4

Range Stop

ORTEC 9308 PICOSECOND TIME ANALYZER

AZ

2   1

Detector Boundary

Ø

EL

Satellite Image

ß = Magnitude of angular error

3   4

PHOTOCATHODE VIEW

Table Lookup for X_O and Y_O

$$f_T(Y_O) = \frac{1}{2\pi}\left[\cos^{-1}[2Y_O^2 - 1] + 2Y_O\sqrt{1 - Y_O^2}\right]$$

$$f_R(X_O) = \frac{1}{2\pi}\left[\cos^{-1}[2X_O^2 - 1] + 2X_O\sqrt{1 - X_O^2}\right]$$

(uniform spot)

Angular Error

Magnitude: $\beta = \dfrac{1}{2F_\#}\dfrac{d/f}{1+d/f}\sqrt{X_O^2 + Y_O^2}$

Orientation: $\emptyset = \tan^{-1}(Y_O / X_O)$

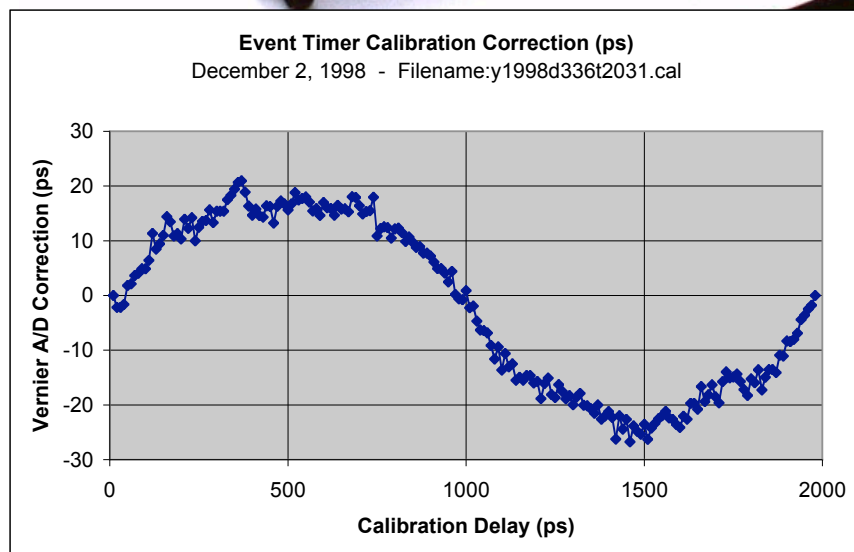| Fraction of Signal Counts	Number of Counts
$f_T = \dfrac{1}{2} + \dfrac{N_T - N_B}{N_T + N_B}$	$N_T = N_1 + N_2$
$f_B = 1 - f_T$	$N_B = N_3 + N_4$
	$N_R = N_1 + N_4$
	$N_L = N_2 + N_3$
$f_R = \dfrac{1}{2} + \dfrac{N_R - N_L}{N_R + N_L}$	T=Top
	B=Bottom
$f_L = 1 - f_R$	R=Right
	L=Left

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SLR 2000 Enhanced Event Timer
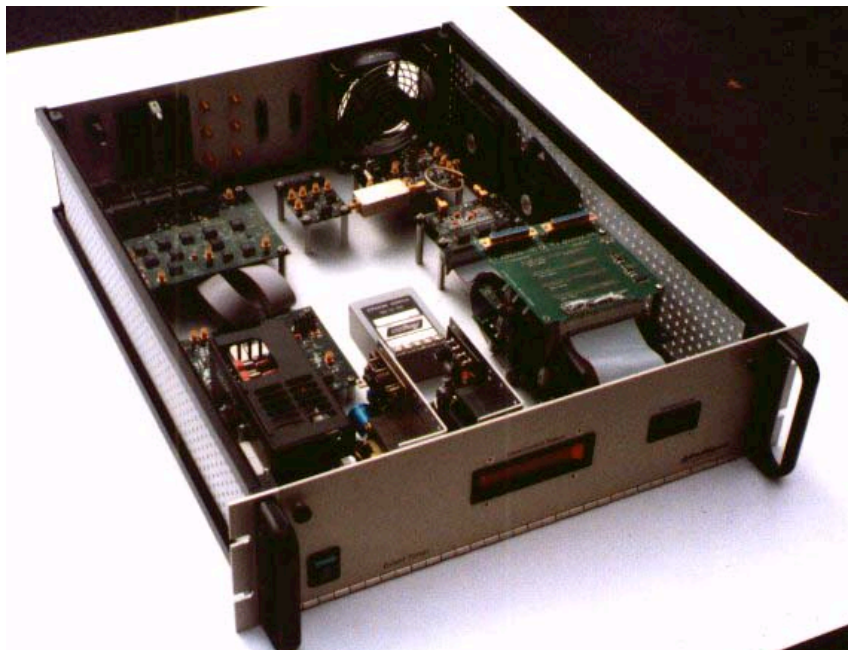
Features

- Clock Speed: 500 MHz
- RMS Jitter: <5 ps (calibrated)
- RMS Range Precision: <1 mm
- Max Event Rate 10 MHz Burst with duration limited by computer (<100 nsec "dead time")
- Internal Data Buffer: 500 events
- Quad Input with Digital ID of input port
- Internal Coarse Clock 500 MHz
- 12-bit A/D sampling over 2 ns period

Event Timer Calibration Correction (ps)
December 2, 1998 - Filename:y1998d336t2031.cal

Event Timer Calibration Error (ps)
December 2, 1998 - Filename:y1998d336t2031.cal

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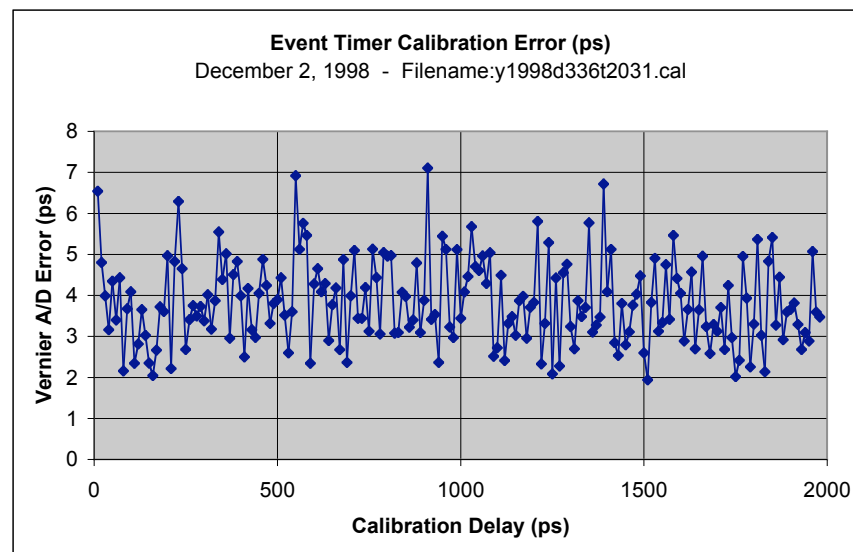
SLR2000 Range Gate Generator

Channels: 4 independent channels, upgradable to 8

Channel Resolution: 20 ps leading edge, 500 ps trailing edge

Coarse Clock: 250 MHz

RMS Jitter: < 50 ps (typically about 20ps)

Range: 20 ns to infinity

Update Rate: Multi-MHz limited by computer interface

RMS jitter of RGG output

◆ Se

15
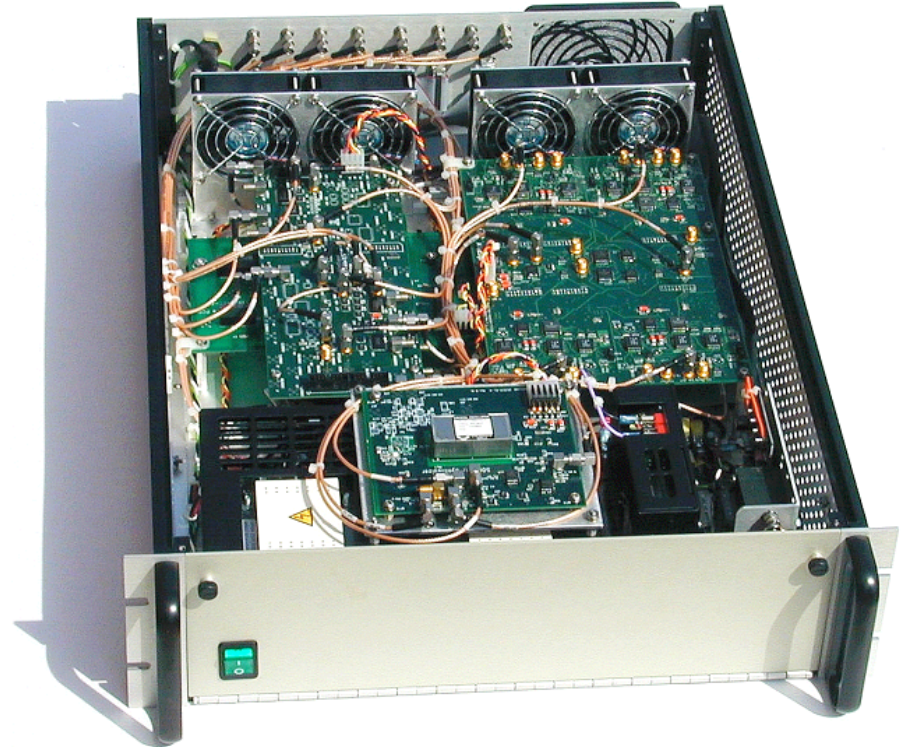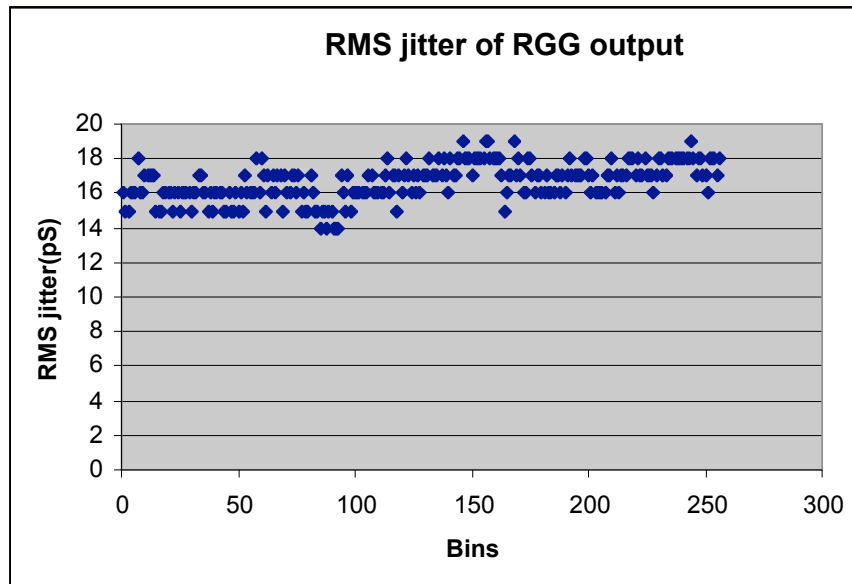
SLR 2000 "Smart" Meteorological Station

- **Wind Monitor**
  - **Belfort 200 (Cost: $800)**
  - **Wind speed -Range: 0 to 135 mph; Accuracy: $\pm$ 0.6 mph**
  - **Wind Direction: Range: 0 to 360º; Accuracy: +3º**
- **Pressure/Temperature/Humidity Monitor**
  - **Paroscientific MET3-1477-001 (Cost: $3,995)**
  - **Pressure:Range: 800 to 1100 mbar; Accuracy: ~0.1 mbar; stability<0.1 mbar/yr**
  - **Temperature: Range: -40 to 70 ºC;Accuracy<0.5 ºC; Stability <0.1 ºC/yr;**
  - **Relative Humidity: Range: 0 to 100%; accuracy:$\pm$2%; stability: <1%/yr**
- **Precipitation/Visibility Sensor**
  - **Vaisala FD12P (Cost: $ 17,895)**
  - **Measures visibility from 10 m to 50 Km**
  - **Measures type, intensity, and accumulation of precipitation**
- **All-Sky Cloud Sensor**
  - **Inframetric Thermasnap^{TM} Thermal Infrared Camera (8 -12 microns) senses ~ 25ºF temperature difference between clouds and clear sky via electroformed convex mirror (Cost : $20,000)**
- **Total Subsystem Hardware Cost: $42,690**
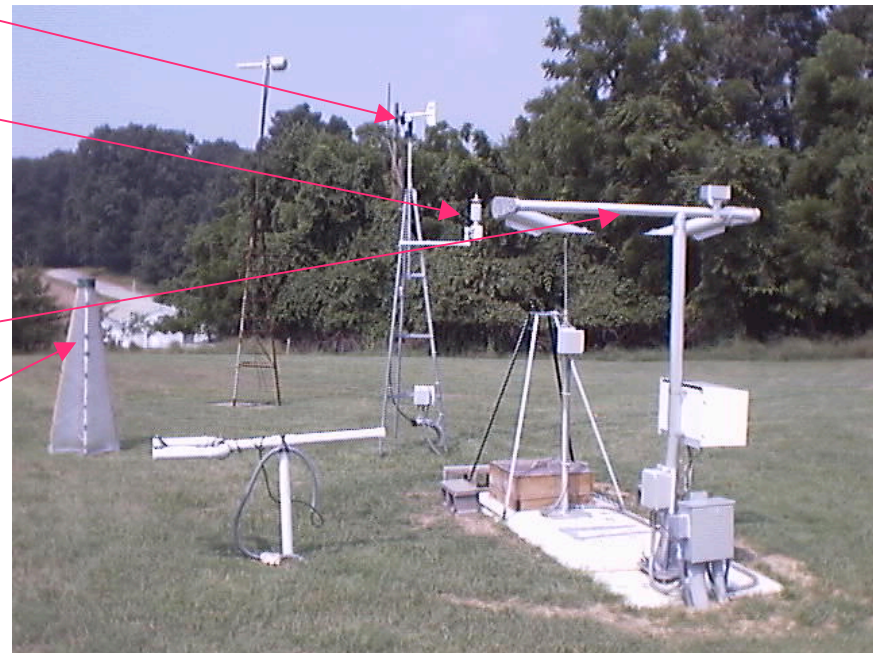
**"Smart" Meteorological Station at GGAO/GSFC**

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SLR2000 Day/Night All-Sky Cloud Sensor
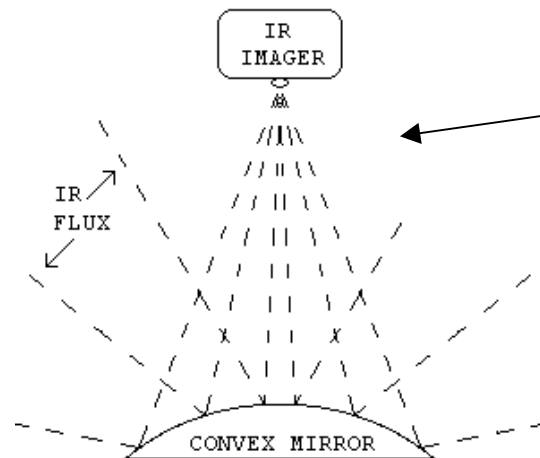
Schematic of the All-Sky Cloud Sensor where infrared flux from the entire sky is reflected by an electroformed mirror into the uncooled IR imager. Cloud maps, combined with remotely updated satellite tracking priorities and orbit predictions, allow the computer to decide which satellites it can and should track.

Color codes:
warmer = blue, green and red
cooler = gray and black.
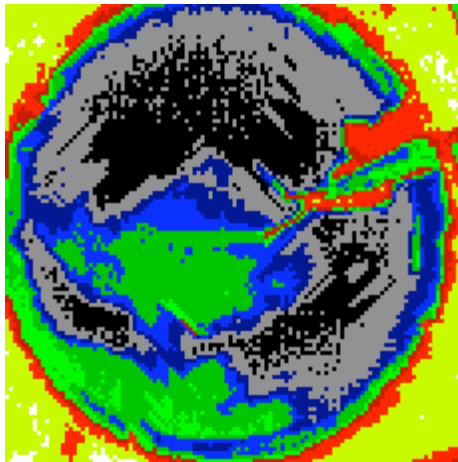
Daylight thermogram shows clear cooler) skies to the north and east. A cloud (warm) covers zenith and extends to the southwest. The red object in the northeast is a support arm. Temperatures are 17 to 33 ^{o}C.
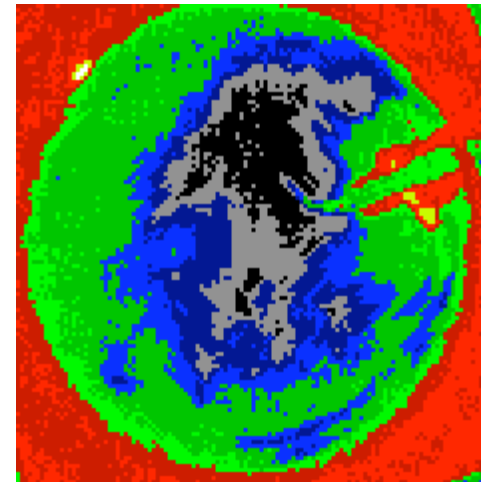
Nighttime thermogram reveals a large patch of clear sky at zenith, extending to the north and south. The east and west are cloudy. Temperature range is 4 to 21 ^{o}C.

SLR2000 Precipitation and Visibility Sensing

The Vaisala optics are comprised of an infrared beam and a detector aimed across the beam. Scattering particles in the intersection of the two paths reflect IR light to the detector. These reflections are analyzed and the particles are characterized. The CPU combines this information with temperature data, reports the type and intensity of precipitation, as well as the visibility, and decides whether the dome should be open or closed.

Precipitation Detection
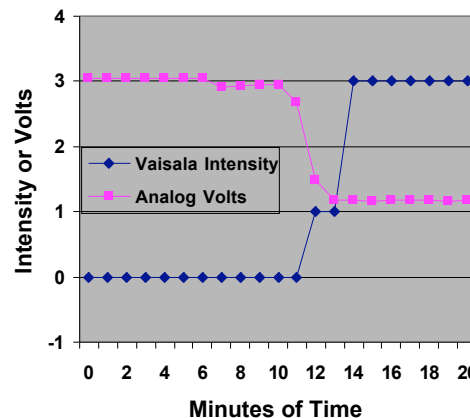
The Vaisala reports precipitation within 2 to 3 minutes of its detection by a sensitive analog device, allowing time to close the dome and protect the equipment.

Histogram of Visibility
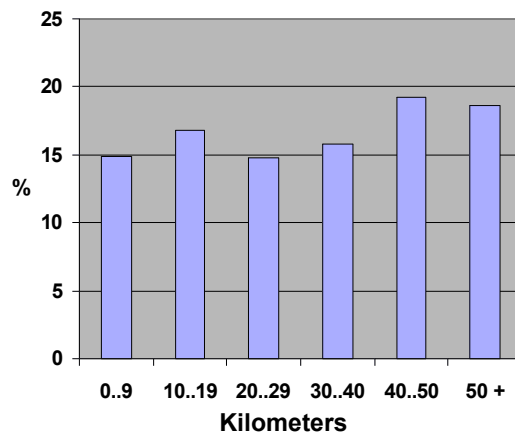
Visibility is defined as the distance that an observer can distinguish a black object against the horizon. At NASA/GSFC, the Vaisala instrument reports a fairly even distribution from 0 to 50 km over a year's time.

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SLR2000 GPS Synchronized Time and Frequency Receiver TrueTime XL-DC 602

- **40 nanosecond Accuracy to UTC with SA**
- **Stability**
  - **1×10^{-9} 1 second**
  - **3×10^{-10} 100 seconds**
  - **1×10^{-12} 1 day**
- **Tracking :**
  - **8 parallel channels**
  - **Multisatellite ensembling with system integrity monitoring**
- **Acquisition Time:**
  - **Warm Start typically <2 minutes**
  - **Cold Start typically <20 minutes**
- **1pps Output**
- **IRIG B Output**
- **Bidirectional RS-232 Port**

XL-DC (SRS Oscillator) vs. MASER

Time Interval In uSec. (1 PPS)

Time (24 hours / 1 minute)

XL-DC (SRS Oscillator) vs. MASER

Time Interval In uSec. (1 PPS)

Time (7 days / 1 minute interval)

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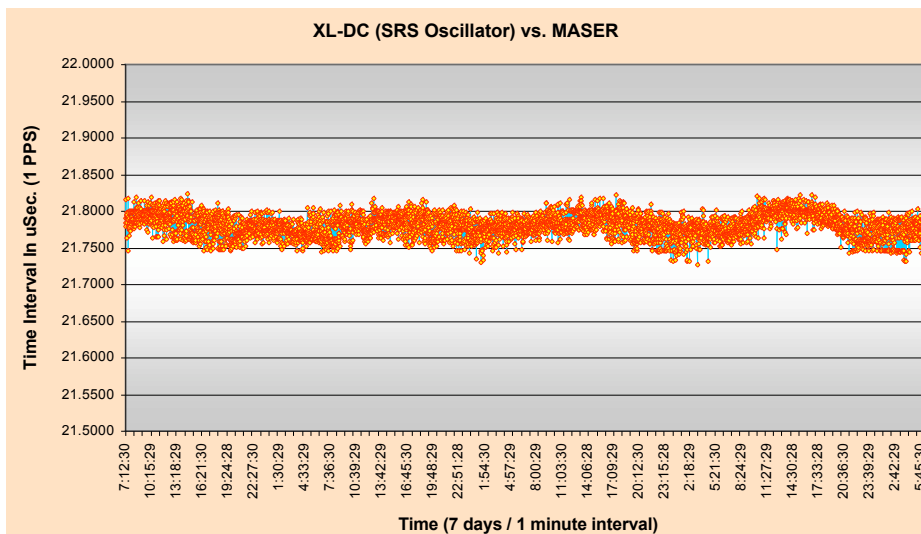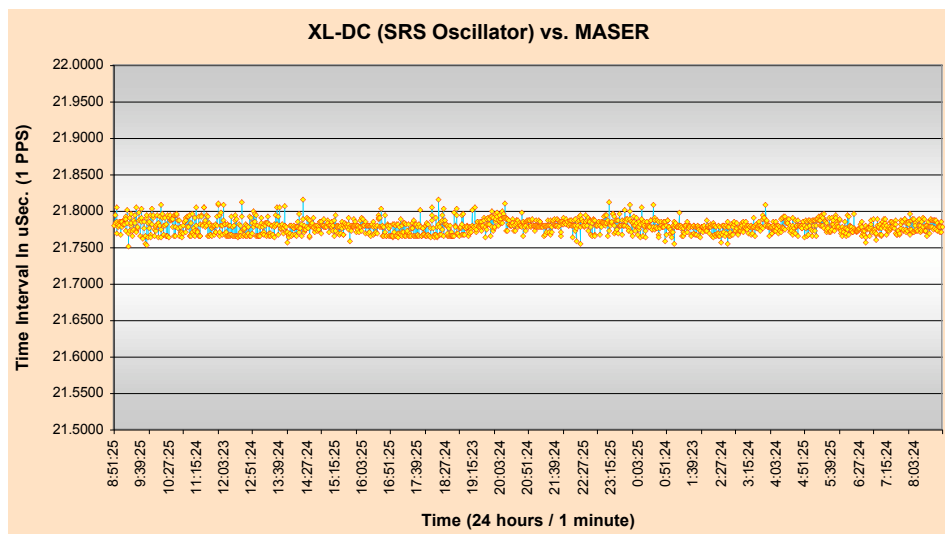
SLR2000 Shelter at GGAO/GSFC Exterior View

3 meter dome
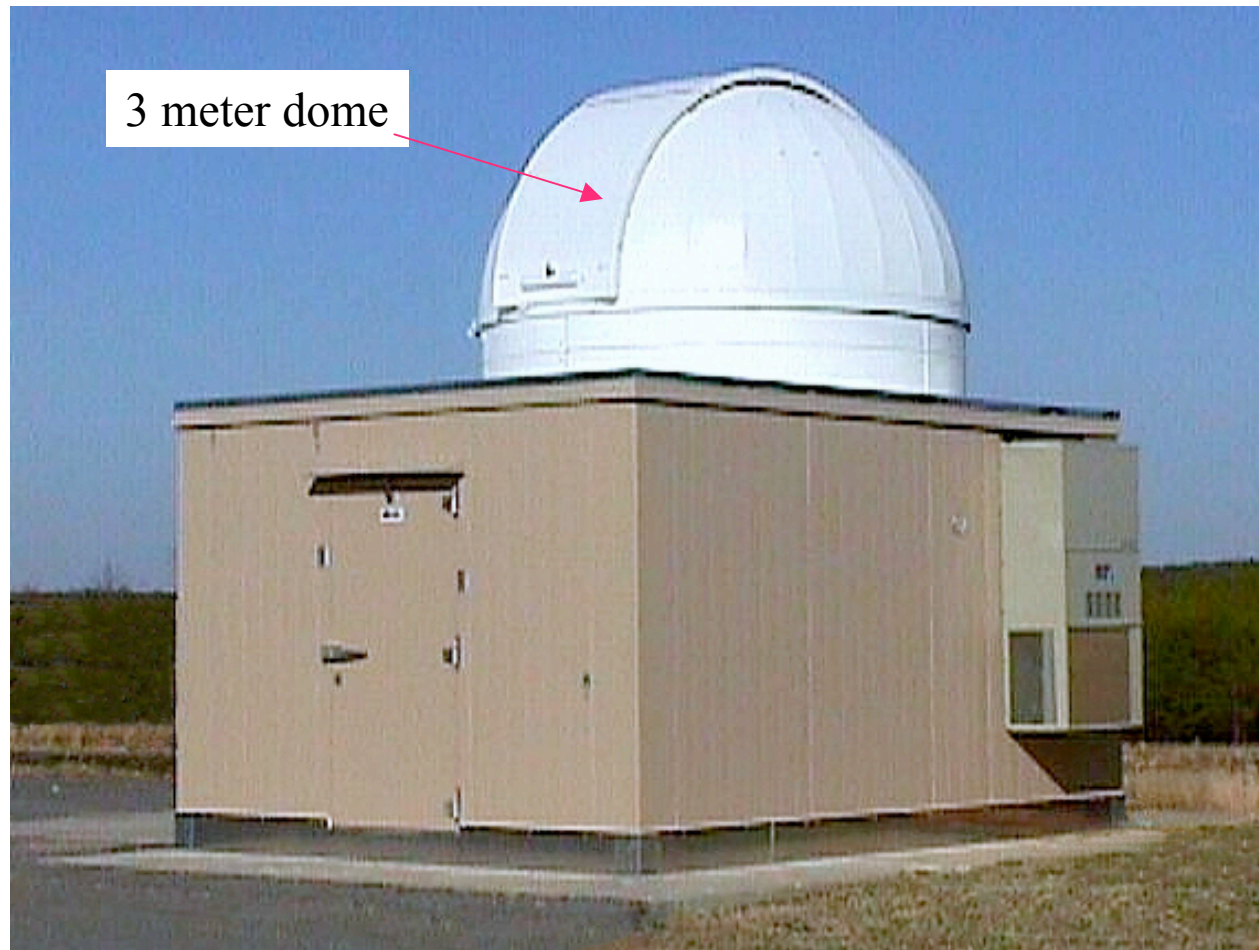
SLR2000 Shelter (Interior View)

Dome Access

Transceiver Bench

Leveling Mounts

Concrete Monument

Stainless Steel Riser
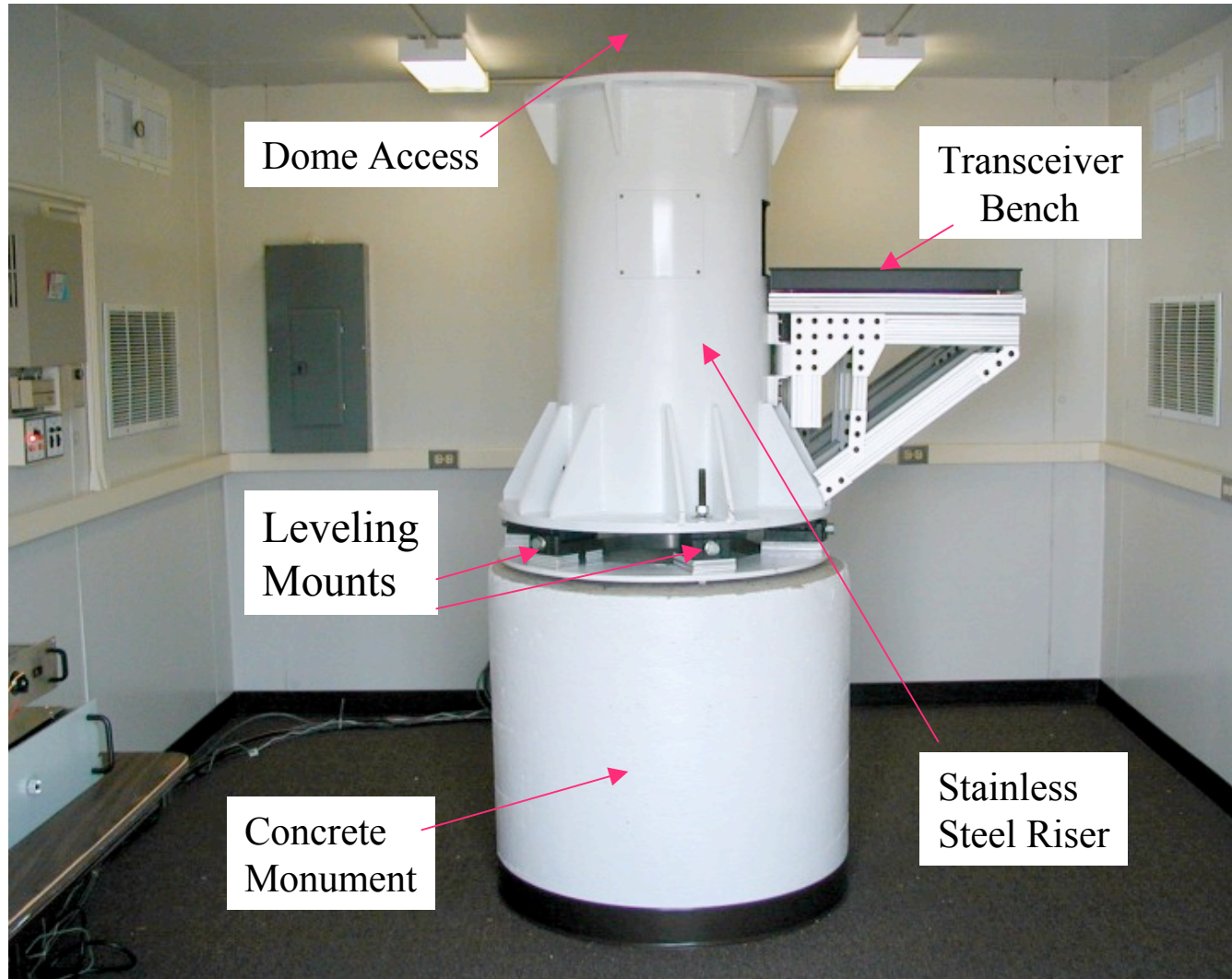
SLR2000 Tracking Mount
(telescope mass simulator installed)
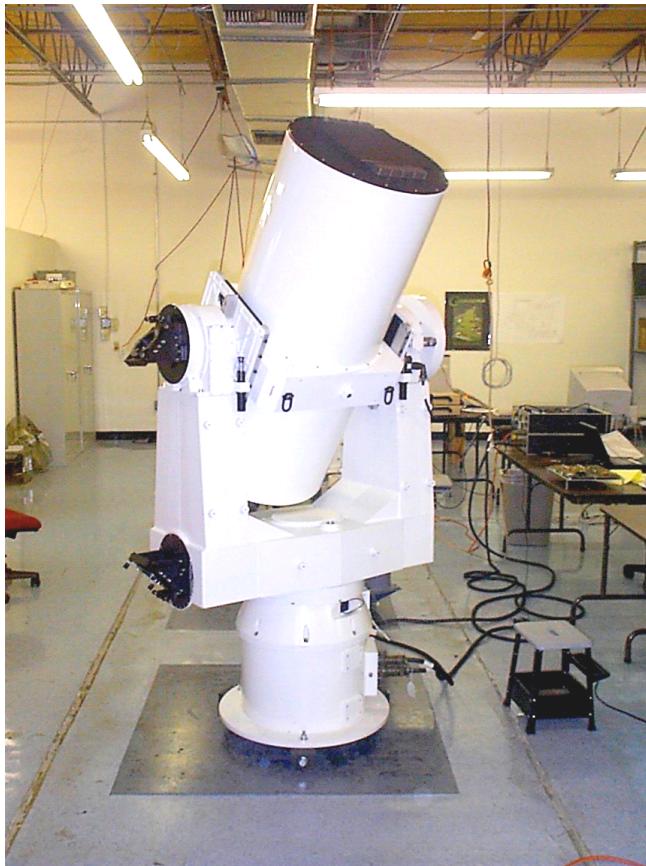
Specifications

- **Slew Rate**
  - **Azimuth: 30 deg/sec**
  - **Elevation: 20 deg/sec**
- **Total Travel**
  - **Azimuth: continuous (slip rings)**
  - **Elevation: -5º to 185º**
- **Maximum Tracking Rate: >5 deg/sec both axes**
- **Minimum Tracking Rate: Sidereal**
- **Maximum Load Acceleration: 5 deg/sec² both axes**
- **Position Resolution: ±0.3 arcsec**
- **Transducer Accuracy: ±1.0 arcsec**
- **Axis Wobble: < 3 arcsec repeatable error**
- **Axis Orthogonality: <5 arcsec repeatable error**
- **Dynamic Tracking Accuracy: <0.7 arcsec RMS**

SLR2000 Telescope Specifications

- **Physical Specifications:**
  - Dimensions: 56" long x 22.5" diameter.
  - Weight: 251 lb.
  - Optics mounted to 4 invar rods for axial stability over wide temperature range.
  - Optics enclosed in a cantilevered inner barrel which is decoupled from the weight of the front window.
  - Minimum resonance: 120 Hz.
  - Surfaces: interior- black anodized aluminum, exterior- white enamel paint.
  - Heaters on front/side windows and desiccant system used for dew mitigation.
  - Telescope O-ring sealed for contamination and moisture control.
  - Air bladder compensates for thermally induced internal pressure changes
  - Sun shield reduces stray light infiltration

- **Optical Specifications:**
  - Off-axis Cassegrain with 17" diameter primary mirror
  - 16" clear aperture
  - 10X magnification
  - Edge obscuration due to secondary: ~9%
  - Performed optical wavefront test through entire telescope system and measured .36 waves rms.
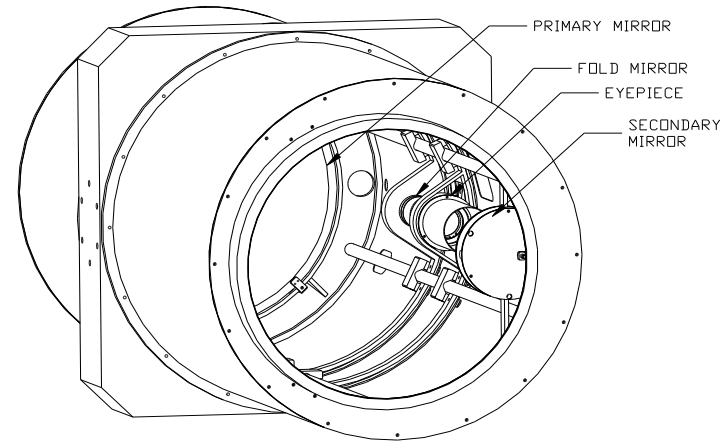
VIEW LOOKING INTO FRONT WINDOW
(SUN SHIELD NOT SHOWN)

9/14/2000

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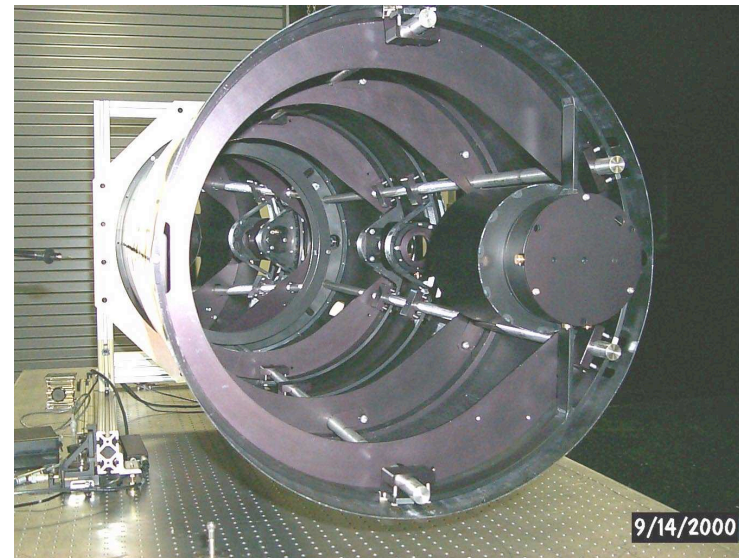
SLR2000 Major Support Subsystems

3 m tracking dome

40 cm off-axis telescope

9/14/2000

Stainless steel riser

Transceiver bench

Concrete monument

Arcsecond Precision Gimbal
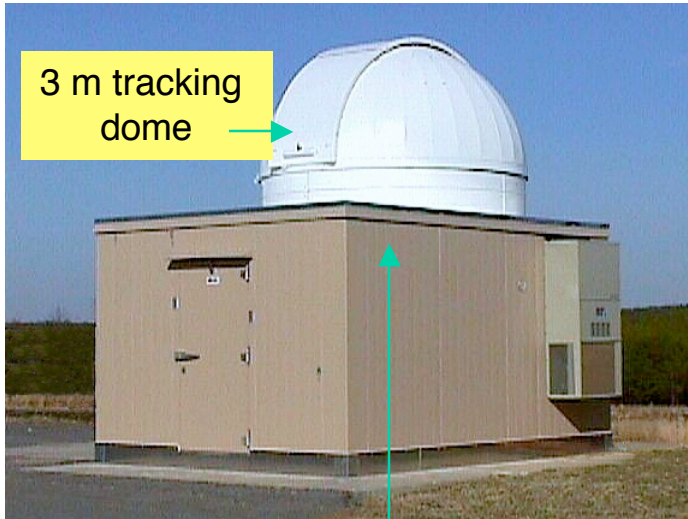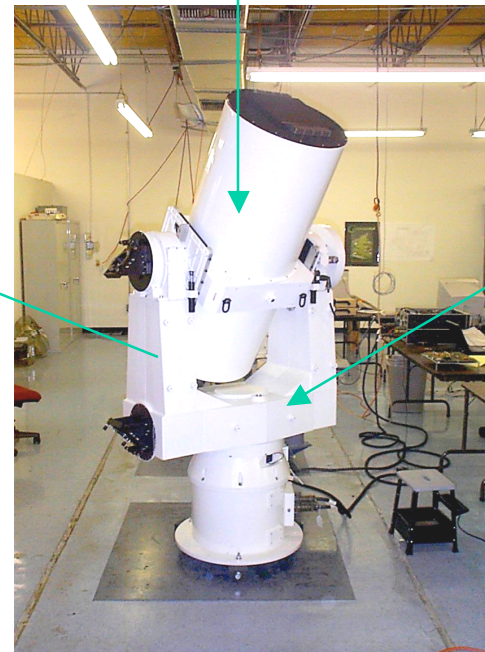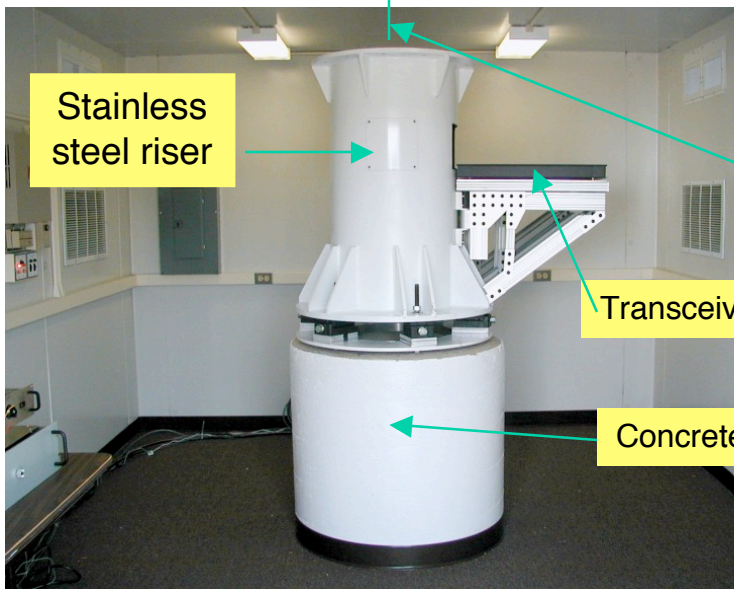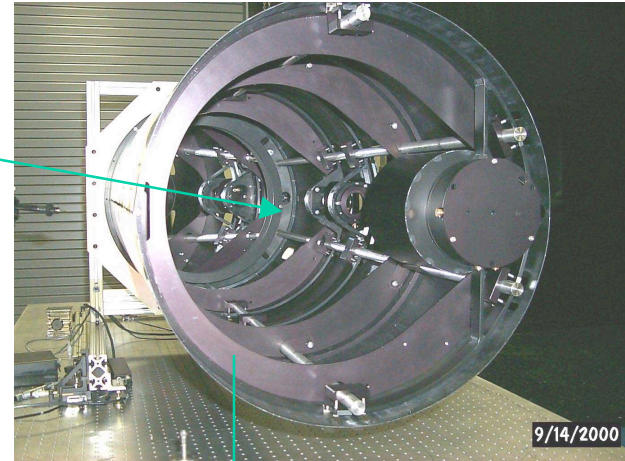
SLR2000 Optical Transceiver
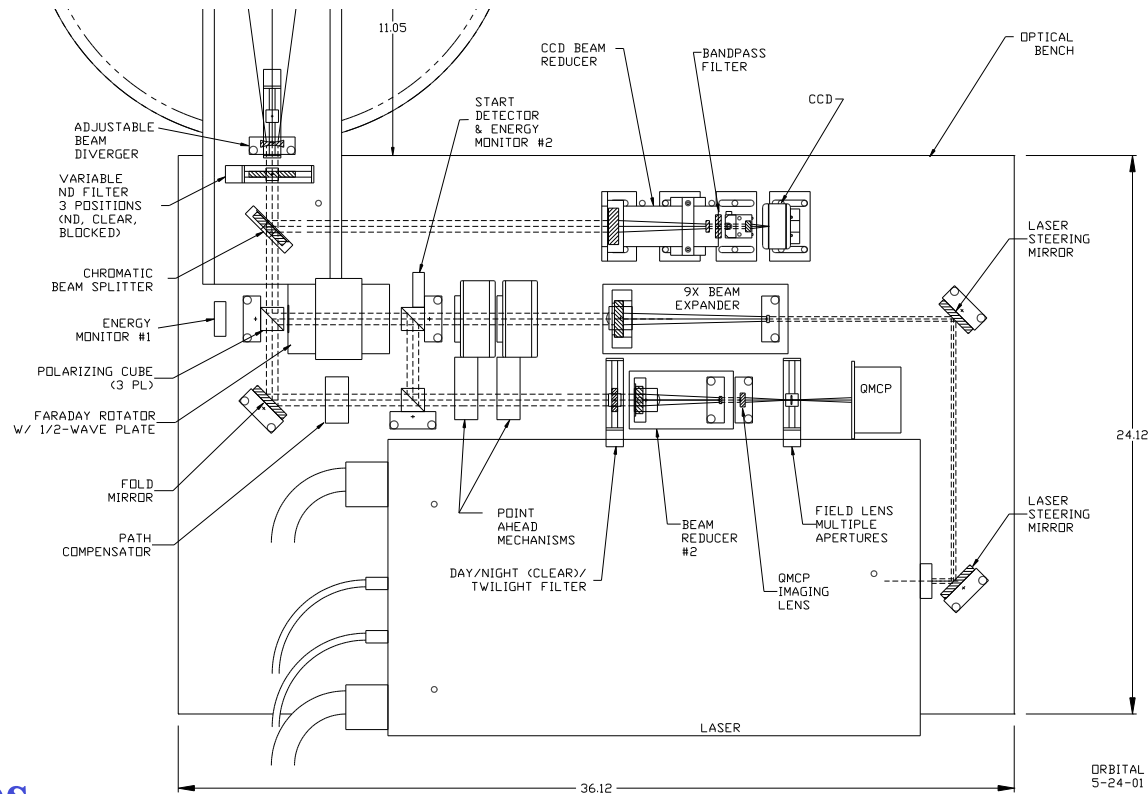
Features

- 36" x 24" x 2" honeycomb optical bench
- Full aperture sharing by transmitter and receiver
- Totally passive, low-loss transmit/receive switch
- Passively Q-switched Microlaser transmitter
- Quadrant Photon-Counting MCP/PMT
- CCD Camera for mount star calibrations

- Automated telescope focus adjustment
- Transmitter point-ahead Risleys (0 to 11 arcsec)
- Spatial and spectral filtering
- Energy monitors
- Alignment and boresighting aids
- Optical attenuator for ground calibrations

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SLR2000 Shelter Layout, Side View

LIGHT

LIGHT

3.00

46.13

23.06

RACK B

RACK A

TIMING/SERVO/DOME CONTROL
BLANK PANEL

MCP/HV P.S.

TRUE TIME

NATIONAL INSTRUMENTS
TIMING SYSTEM

DOME TERN
CONTROLLER

DOME MOTOR
CONTROLLER

ICC
MONITOR

KEYBOARD

ICC

GIMBAL
SERVO
CONTROL
UNIT

UPS

T/R ELECTRONICS/COMPUTERS
BLANK PANEL

DISCRIMINATOR

EVENT TIMER

RANGE GATE
GENERATOR

RECEIVER

SIMULATOR
PACKAGE

TAPE SHELF

VME BREAKOUT PANEL
OPEN SPACE

VME
COMPUTER

HEALTH
&
SAFETY
COMPUTER

UPS

LASER

BREAKER BOX

76.00

72.00

CHILLER

RAISED FLOOR AREA

STEP

14.00

73.63

30.69

26

SLR2000 Rack Elevation

FRONT VIEW

Dimensions: 46.13, 23.06, 73.63, 30.69

RACK B

TIMING/SERVO/DOME CONTROL
BLANK PANEL
MCP/HV P.S.
TRUE TIME
NATIONAL INSTRUMENTS TIMING SYSTEM
DOME TERN CONTROLLER
DOME MOTOR CONTROLLER
ICC MONITOR
KEYBOARD
ICC
GIMBAL SERVO CONTROL UNIT
UPS

RACK A

T/R ELECTRONICS/COMPUTERS
BLANK PANEL
DISCRIMINATOR
EVENT TIMER
RANGE GATE GENERATOR
RECEIVER
SIMULATOR PACKAGE
TAPE SHELF
VME BREAKOUT PANEL
OPEN SPACE
VME COMPUTER
HEALTH & SAFETY COMPUTER
UPS

SIDE VIEW

Dimension: 31.56

SLR2000 Shelter Layout, Overhead View

OUTLET STRIP

60 INCH TABLE

HVAC CONTROL

RAISED FLOOR AREA

BREAKERS

STEP

JOHN

LASER

TOM

OUTLET STRIP

ANTISTATIC CHAIR MAT

TIMING, ICC, MONITOR/KEYBOARD,
RACK B
DOME & SERVO CONTROLLER

T/R ELECTRONICS,
RACK A
COMPUTERS, UPS

RAISED FLOOR AREA

STEP

36 INCH TABLE

JAN

ANTISTATIC CHAIR MAT

ANTISTATIC CHAIR MAT

36 INCH TABLE

OUTLET STRIP

28

SLR2000 Site Layout

PUMP HOUSE

TRANSFORMER

BURIED TANK

WEATHER INSTRUMENTS SITE LAYOUT

VAISALA

WEATHER STATION

MET 3

TRUE TIME GPS ANTENNA

6'

NORTH

8'

20'

30'-6.00"

EXSISTING CONCRETE PAD

EXSISTING CONCRETE PAD

SKY CAMERA MOUNTED ON 4 FOOT SQUARE ELEVATED CONCRETE PLATFORM

HVAC

HVAC

DOME

PARKING SPACE

PARKING SPACE

PARKING SPACE

EXSISTING CONCRETE PAD

SHELTER

EXSISTING CONCRETE PAD

ROADWAY

29

SLR2000: Current Subsystem Open Items

- **Facility**
  - Complete Dome Environmental Control
  - Complete Dome Shutter Fabrication and Control
  - Install Health & Safety Subsystem

- **Meteorological Station**
  - Upgrade All-Sky Cloud Sensor (improved camera and mirror)

- **Tracking Gimbal**
  - Complete and implement software modeling to meet 0.7 arcsec RMS dynamic tracking spec

- **Telescope**
  - Complete mass properties test and checkout dessicant system
  - install and align in gimbal mount

- **Laser Transmitter**
  - Procure upgraded OSC/AMP transmitter

- **Optical Transceiver**
  - Complete procurement, assembly, and internal alignment
  - Install and align to gimbal/telescope

- **Range Receiver**
  - Complete lab tests under software control

SLR2000 PROJECT MASTER SCHEDULE

5/30/01

	2001									2002									
	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct

MAJOR MILESTONES — System Integ. Cpt. (Nov); System Verification Cpt. (Sep 2002)

SUBSYSTEM DEVELOPMENT

- Facility — Dome & Controller; Thermal Control; Health & Safety
- Gimbal Tracking Mount — Delivery
- Optical Transceiver — Delivery; Laser Upgrade
- Telescope — H/W Cpt.; Deliver to GGAO
- Range Receiver — H/W Cpt.; S/W Subsys. Test; Verification Cpt.
- Meteorological System — Cloud Sensor Upgrade
- Computer — ISA/ PCI; Health & Safety
- Software Development — Ver 0.9; Ver 1.0; Ver 2.0; Ver 3.0; Ver 4.0
    - Operational Package
- Simulation Testing

PROTOTYPE INTEGRATION & TEST

- Meterological Station & Equipment Move/ Verification
- Install & Align Gimbal & Optical Transceiver
- Perform Subset of Gimbal Factory Acceptance Test
- Install Telescope & Align System
- Gimbal Field Acceptance Test

SYSTEM FIELD TESTING

- Star Calibration
- Satellite Visual Tracking
- Calibration Ranging
- Satellite Tracking
- Collocation Test w/ MOBLAS 7

Summary: SLR2000 Future Plans

- **FY01**
  - Complete tracking mount mods and demonstrate 0.7 arcsec RMS tracking precision
  - Install tracking mount in facility and integrate the telescope
  - Fabricate and integrate optical transceiver
  - Begin transmitter upgrade : shorter pulsewidth, more energy, more compact packaging, no water cooling
  - Upgrade all-sky cloud sensor: install electroformed reflectorfor improved sky imaging, improved environmental packaging for infrared camera
  - Begin installation of health, safety, and security subsystems
  - Begin system field tests

- **FY02**
  - Complete and install upgraded field laser
  - Complete system field tests and documentation

- **FY03 and beyond**
  - Replicate 8 to 12 NASA units plus any outside purchases through FY06
  - Perform R&D on two color version for reducing atmospheric refraction contribution to range error
  - Pursue SLR2000 spinoff applications

- **SLR2000 Spinoffs**
  - IIP Airborne Multikilohertz Microlaser Altimeter (currently funded by NASA IIP program)
  - Laser transponders for precise interplanetary ranging and time transfer (GSFC DDF)
  - Subsystems are applicable to ground to satellite optical communications and automated ground lidars